Optics, Acoustics, and Stress in a Nearshore Bottom Nepheloid Layer

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LONG-TERM GOALS

The goal of this research is to develop greater understanding of the how the flocculation of fine-grained sediment responds to turbulent stresses and how this packaging of sediment affects optical and acoustical properties in the water column.

OBJECTIVES

1. Quantify the effects of aggregation dynamics on the size distribution of particles in the bottom boundary layer;

2. Quantify how changes in particle packaging affect the optical and acoustical properties of the water column.

3. Develop models describing the associations between particle aggregation, stress, and the acoustical and optical fields.

APPROACH

The approach is to obtain measurements that will permit comparisons of temporal evolution of bottom stress, suspended particle size, and optical and acoustical properties in the bottom boundary layer. The instrumentation is mounted on 2 bottom tripods and an I-beam frame. The "OASIS" tripod includes a 9-wavelength optical attenuation and absorption meter (WetLabs ac-9, with automated dissolved measurement for calibration-independent particulate measurements), LISST-100 (Type B) and LISST-Floc laser diffraction particle sizers (Agrawal & Pottsmith 2000), a digital floc camera (DFC) (Curran et al. 2002), an AquaScat 4-frequencies Acoustic Backscattering Sensor and a Tracor Acoustic Profiling System (TAPS) (Holliday 1987). Near-simultaneous ac-9 measurements with and without a filter assure high-quality particulate spectral absorption and attenuation measurements. The LISSTs and DFC together provide particle size distributions from 1.25 μm to 1 cm in diameter. The TAPS and AquaScat obtain range-gated, vertical profiles of acoustical backscatter intensity at a range of frequencies between 0.3 and 4.0 MHz. These data can be used to generate particle size distributions (Holliday, 1987; Hay and Sheng, 1992). Single frequency acoustic and optical and backscattering sensors are also deployed to enlarge the range of measurements and evaluate the use of commercial instrumentation such as acoustic current meters (ADV and MAVS) for measurements of suspended particle concentration. In 2006-2007 a new tripod was constructed and deployed. It is called the Modified In Situ Size and Settling Column Tripod (MINSSECT). It was developed to provide better constraint on conversions between optical signals, particle area, and particle mass. It carries a digital floc camera, a LISST-100 (Type B), a video settling column, and an automated water transfer system. The equipment on this tripod monitors in situ particle size distribution from 1.25 μm to 1 cm in diameter and size versus settling velocity for particles larger than approximately 100 μm. The water transfer system provides direct estimates of the mass in suspension that can be used to calibrate the beam attenuation coefficient to suspended mass. The I beam array consisits of 4 of SonTek/YSI acoustic Doppler velocimeters (ADVs) mounted vertically ~ 0.25 m above the bottom.

The combined optical and acoustical measurements provide a comprehensive description of the suspended particles near the seabed. The velocity measurements obtained from the ADVs provide direct-covariance estimates of Reynolds stress and inertial-range estimates of the dissipation rate for turbulent kinetic energy (Trowbridge 1998; Trowbridge and Elgar, 2001; Shaw and Trowbridge, 2001; Trowbridge and Elgar, 2003).

Boss, Hill, and Milligan collaborate closely on this project. Together they are providing data and models on the flocculated size distribution of suspended sediment and on the optical and acoustical properties of the water column. Boss has responsibility for deployment of optical and acoustical sensors, and he is responsible for the deployment of the LISST-100 Type B and LISST Floc. Milligan and Hill have responsibility for the DFC on the OASIS tripod and for the entire MINSSECT. Wayne Slade is a graduate student at UMaine. Jim Loftin (UMaine), Brent Law (BIO) and Kristian Curran (Dal) provide support in the lab and field. Additionally, Clemantina Russo, a graduate student at UMaine with only partial funding from OASIS, is working on the link between acoustic backscattering measured by ADV and the concentration and size of scatterers.

We also collaborate with John Trowbridge (WHOI) on this project. He is responsible for characterizing the stress in the bottom boundary layer during the deployments. We also collaborate with Oscar Schofield (Rutgers) who deployed gliders in the study area during our September 2007 deployment. A group from WetLabs deployed a profiling mooring during part of our September 2007 deployment. Yogi Agrawal (Sequoia Scientific) placed a prototype "LISST Back" on MINSSECT for part of our September 2007 deployment.

WORK COMPLETED

Work was completed in four areas during 2007. First, analysis of data from a 2005 deployment continued. Second, equipment was prepared and deployed for approximately 1 month in September, 2007. Third, experimentation was carried out to examine the effect of floc breakage on particle size distribution and beam attenuation. Finally, modeling of the vertical gradient of beam attenuation in a bottom boundary layer was refined, and predictions were compared with archived data.

The analysis of 2005 data is nearly complete. Work-up of the stress data was delayed, which slowed progress toward the overall goal of linking particle size, optics, acoustics and stress.

The MINSSECT was designed and built at Bedford Institute of Oceanography during the year. A new camera for the OASIS tripod was also constructed. It was designed to increase temporal resolution of our time series of images and to allow burst sampling capable of resolving changes in the particle size distribution associated with the passage of individual waves. The AquaScat acoustic scattering system was upgraded and calibrated with glass beads at the manufacturer, and preliminary data look promising.

The tripods and stress array were deployed on September 1, 2007. The MINSSECT was recovered and re-deployed repeatedly until final recovery on September 24, 2007. The OASIS tripod was serviced (windows cleaned and filters changed) repeatedly until it was disconnected on September 24, 2007. The stress array was in the water throughout this deployment. Data recovery was excellent for all instruments.

To gain a better understanding of floc breakage, in the summer of 2007 we performed several experiments where we deployed two similar LISST instruments (a LISST-100 and a LISST-100x both of type B) side by side. We used a pump to break aggregates and measured those with one of the LISSTs while the other was open to the environment.

We have refined a steady, 1-D model of optical attenuation in continental-shelf bottom boundary layers. The model is an adaptation of Pat Wiberg's successful model (Wiberg et al., 1994). The only differences between our model and Wiberg's are the incorporation of a stress-dependent aggregate-packaging term and a reduced active-layer thickness. Most importantly, however, is the inclusion of direct modeling of optical properties based on particle mass and size distribution. The Wiberg model relies on empirical correlation to relate particulate mass to optical attenuation.

Modeling of the optical properties of oceanic aggregates is in progress. Very little has been done on this subject in ways applicable to natural marine aggregates because most previous work assumes primary particles are much smaller than the wavelength of light.

RESULTS

From our 2005 deployment the merged volume concentration and area concentration (i.e. cross-sectional area) distributions were apportioned into single grain (<36 μm in diameter), microfloc (36 – 133 μm in diameter), and macrofloc (>133 μm in diameter) fractions (Mikkelsen et al., 2006). In general, as bottom shear stress increases, the fraction of single grains increases and the fraction of macroflocs decreases (Figures 1 and 2). We interpret this trend as an indication of floc breakage forced by elevated shear stresses. When stresses are low, a wide range of single-grain and macrofloc fractions are possible. This suggests that biological processes may play a large role in determining the presence or absence of large flocs at low stresses. As reported previously, changes in the relative abundance of large flocs changes the spectrum of light attenuation as well. Abundant large flocs flatten the attenuation spectrum.

The 2007 deployment has just finished. Overall data recovery was excellent. The new DFC on the OASIS tripod, however, did not function properly, resulting in a very limited data set. We are exploring the cause of the failure. The DFC on the MINSSECT did function throughout, taking images every 5 minutes. Therefore, excellent full particle size distributions will be available for the entire deployment. The water transfer system collected samples on all MINSSECT deployments providing over 150 calibration points for the full size distribution spectra. Modifications to the settling column appear to have eliminated earlier problems with wave pumping.

In the comparison of particle size distributions from the pumped and un-pumped LISSTS, particulate size distributions when both were deployed side by side without the aggregate break up apparatus were similar (Fig. 3a). However, when pumped, floc breakage occurred, causing a shift of floc mass to smaller particles (Fig. 3b). These results are consistent with the general trend of particle packaging with stress in the 2005 data set. The breakup of flocs has significant effects on beam attenuation; it causes a relative increase in the beam attenuation by ~20% (Fig. 4).

The 1-D steady state model of optical attenuation in a bottom boundary layer in general is able to reproduce observed particulate beam attenuations at a variety of wavelengths. The model does not perform well under two circumstances. As stress falls following a resuspension event, the model under-predicts attenuation because it fails to account for the time required for small, slowly sinking single grains to deposit. The model over-predicts attenuation at times when suspended sediment stratification limits the diffusion of sediment into the bottom boundary layer. Time dependence and stratification effects will need to be incorporated into improved models of particulate beam attenuation in bottom boundary layers.

We have designed a model to study the optical properties of aggregates based on the work of Latimer (1985). The model is based on the average of two models: 1. A coated sphere where the core is water and the outward shell represents the solid fraction and 2. A homogeneous prolate spheroid with a 1/3 axis ratio and an index of refraction. Both models actually give similar predictions (the two curves of in Fig. 5). What we are finding is that aggregation causes beam attenuation to be *less* sensitive to size, thus explaining why it is such a good proxy of suspended material concentration. Aggregated material, because of its large water volume, is much bigger than its component particles and therefore has large geometrical and optical cross sections. A simple modeling exercise where we assume that aggregates are fractal objects composed of inorganic primary particles of 1μm diameter (see Maggi, 2007) shows that the beam attenuation to volume of solid particle ratio (and thus to mass) is not affected strongly by the different aggregates of this primary material (dots in Fig. 5). This is very different than the result one would get for solid particles (which will be similar to the F=0.99 curve in Fig. 5)

IMPACT/APPLICATIONS

The high resolution time series of particle, optical, and acoustical properties will enhance understanding of the rates and mechanisms by which the water column clears following storm events.

Development of 1-D model include the development of a module which converts sediment to optical properties. This advance will provide the sedimentology community a simple tool to test their model predictions against the most ubiquitous measurement of suspended matter in coastal waters.

RELATED PROJECTS

Hill has a project funded by NSERC (Canada) that investigates the effect of in situ particle size distribution on the interaction of oil and sediment in suspension. This project funded the purchase of the LISST-100 on the MINSSECT.

DURIP grant to E. Boss (N000140410235) provides instrumentation used in the present project.

Boss has a project with Agrawal (N00014-04-1-0710) to study optical scattering from natural (e.g. non-spherical) particles and develop a new scattering sensor which we deployed on the OASIS tripod during our last field work.

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PUBLICATIONS

Slade, W.H., Boss, E.S. 2006. Calibrated near-forward volume scattering function obtained from the LISST particle sizer. Optics Express, 14: 3602-3615. [published, refereed]

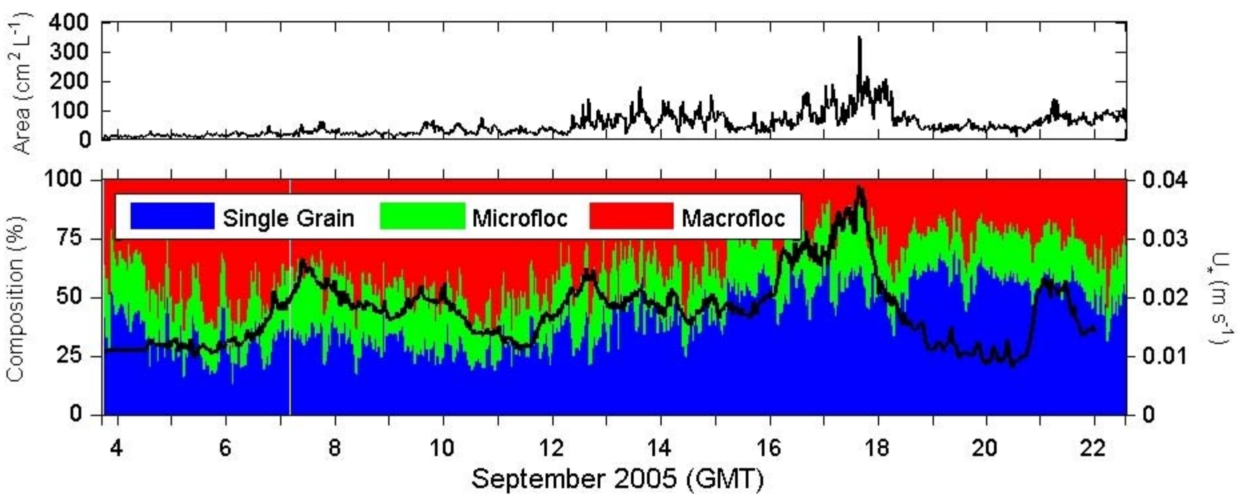

Figure 1. Time series of suspended particle area (top panel) and size partitioning and shear velocity (bottom panel) during the September 2005 deployment. In the bottom panel shear velocity is shown by the black line. In general area in suspension is correlated with shear velocity, indicating that resuspension supplies sediment to the bottom boundary layer. Also, the fraction of macroflocs in suspension tends to decrease as shear velocity increases, while the concentration of single grains increases with increasing shear velocity. At low shear velocities, partitioning of area among single grains, microflocs, and macroflocs is variable.

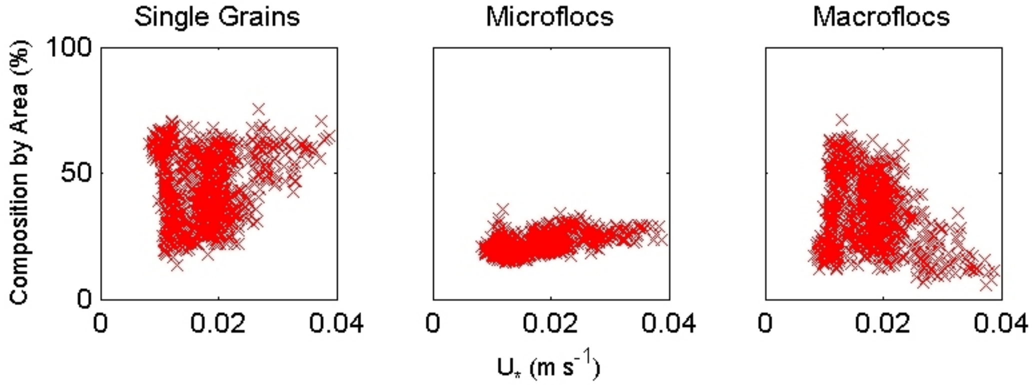

Figure 2. Scatterplots of the partitioning of area among three size groupings as a function of shear velocity for the September, 2005 deployment. Single grain fraction is variable at low shear velocity, but is restricted to values of approximately 50% at high shear velocity (left panel). Microfloc areal fraction is relatively constant at approximately 20% (middle panel). The fraction of macroflocs is variable at low shear velocity, but is restricted to values approximately 10% at high shear velocity.

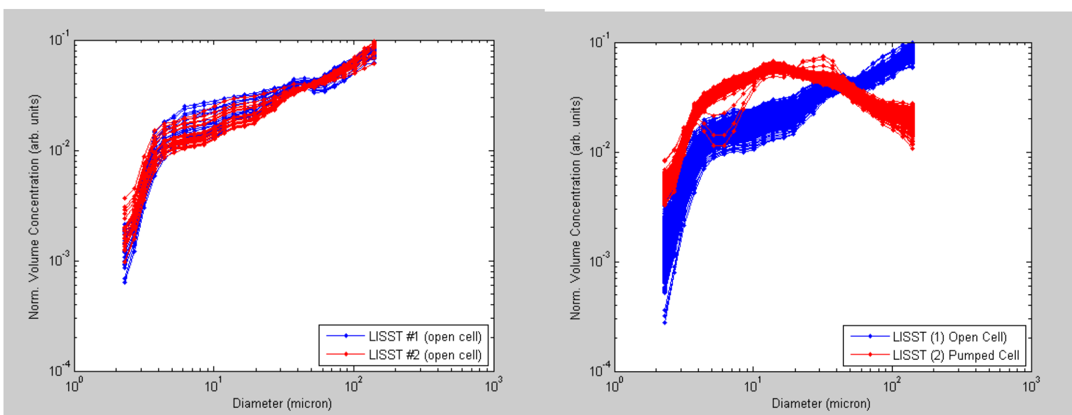

Figure 3. Particle size distribution (PSD) derived from two LISST instruments. When both instruments are deployed similarly they provide similar PSDs. When one is pumped the PSDs are widely different and significant mass passes from aggregates bigger than 50μm to smaller aggregates and primary particles (b).

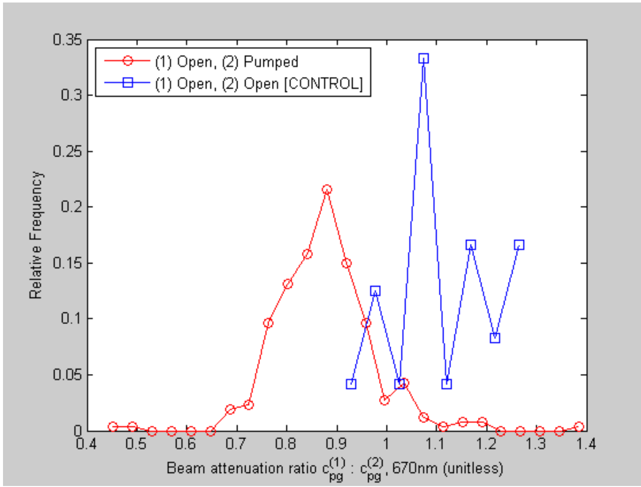

Figure 4. Histogram of the ratio of the beam attenuation from two LISST instruments when both were deployed similarly (blue) and when one was pumped (red). Significant increase in the beam attenuation by the pumped instrument (and thus a decrease in the ratio of unpumped to pumped) is observed.

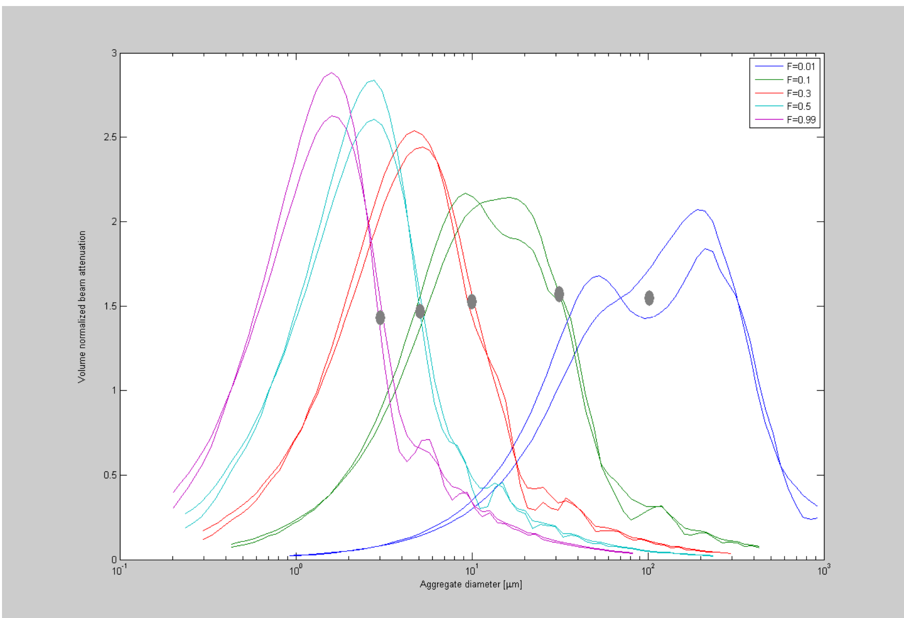

Fig. 5. Curves of beam attenuation to solid fraction volume ratio for aggregate with different solid fraction F. The two different lines represent two different models suggested by Latimer to be averaged for an aggregate model. The dots represent the values one would get if the primary particle is assumed to be 1μm and using relation of fractal dimension and aggregate size as in Maggi (2007).